Two-Step Capacity Modulation of a Single Cylinder Compressor

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TWO-STEP CAPACITY MODULATION OF A SINGLE CYLINDER COMPRESSOR

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Abstract:

Energy efficiency will become an increasing concern in the next decade, and disproportionately so for small, single cylinder compressors because of their widespread use in consumer products. An effective way to dramatically improve system efficiency is through the use of capacity modulation.

Through the use of a special mechanism, a single-cylinder reciprocating compressor can provide two-step capacity modulation for little added cost. Many of the benefits of fully-variable capacity can be achieved with two-step modulation: improved system efficiency, decreased cycling and improved temperature control. This can be done in a cost-effective manner and can be easily adapted to existing appliances.

INTRODUCTION

Single cylinder compressors are used in a wide array of refrigeration equipment. They can be found in such commercial appliances as water coolers, water fountains, vending machines and ice machines as well as consumer products like refrigerators, freezers and air conditioners. There are several forces that are driving these compressors to become more efficient. The EPA regulated phase-out of ozone-depleting chemicals means that both the working fluids of refrigeration systems (1996) and the insulation of cabinets (2003) are changing, usually to less effective alternatives. In addition, the energy efficiency standard for refrigerators is being raised (2001). Coupled with these monumental changes are the facts that many refrigeration products sell today for a price similar to that of twenty or thirty years ago, and that consumers are demanding more technology and features for a very small increase in price.

There are several ways to attack this multi-faceted problem of efficiency, cost, consumer features and environmental impact. Research is underway to develop working fluids that are more efficient and less detrimental to the environment. Replacement blowing agents for phased-out chemicals are being investigated to improve cabinet insulation performance. Cabinets can incorporate more insulation resulting in thicker walls and decreased interior volume. Electronic controls can be used to better control efficiency, cooling and to provide consumer features such as faster cooling and ice making. Capacity modulation can also provide improved efficiency and consumer features for varying amounts of increased cost.

Capacity modulation can be achieved by several techniques. Hot-gas bypass, compressor speed modulation, multiple compressor configurations, variable displacement compressors, variable expansion devices and fan speed modulation are commonly used techniques. Two-step capacity modulation of an individual compressor is a new technology that can be employed to great benefit for minimal applied cost.

Two-step capacity modulation in a single-cylinder compressor can be achieved through the use of an additional component in a standard reciprocating compressor. This modulating compressor contains a crankshaft, an eccentric bushing (throwblock) and a connecting rod as shown in Figure 1 below. It is this throwblock that controls the capacity modulation of the compressor.

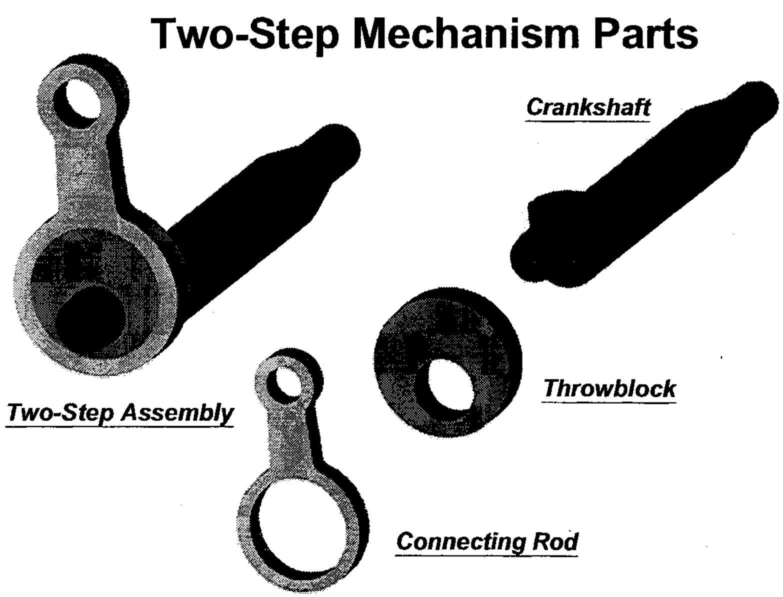

Figure 1

OPERATION OF THE TWO-STEP MECHANISM

The two steps of capacity modulation are achieved through control of the piston stroke, or the swept volume. In full capacity mode the piston sweeps the entire cylinder volume from Top Dead Center (TDC) to Bottom Dead Center (BDC). In partial capacity mode the piston sweeps only a portion of the cylinder volume from TDC to some preset intermediate point. The stroke of the piston is controlled by the throwblock.

The throwblock controls the stroke of the piston by attaching to either the crankshaft or the connecting rod. When the throwblock is attached to the crankshaft, it rotates with the crankshaft and the piston stroke equals the eccentricity of the crankshaft plus the eccentricity of the throwblock. This is the full capacity mode. When the throwblock is fixed to the connecting rod, the piston stroke equals only the eccentricity of the crankshaft, as in a standard compressor. This is the partial capacity mode. In both modes, the throwblock is fixed such that the piston comes to Top Dead Center (TDC) of the cylinder. The motion of the throwblock in each mode is illustrated in Figures 2 and 3 below.

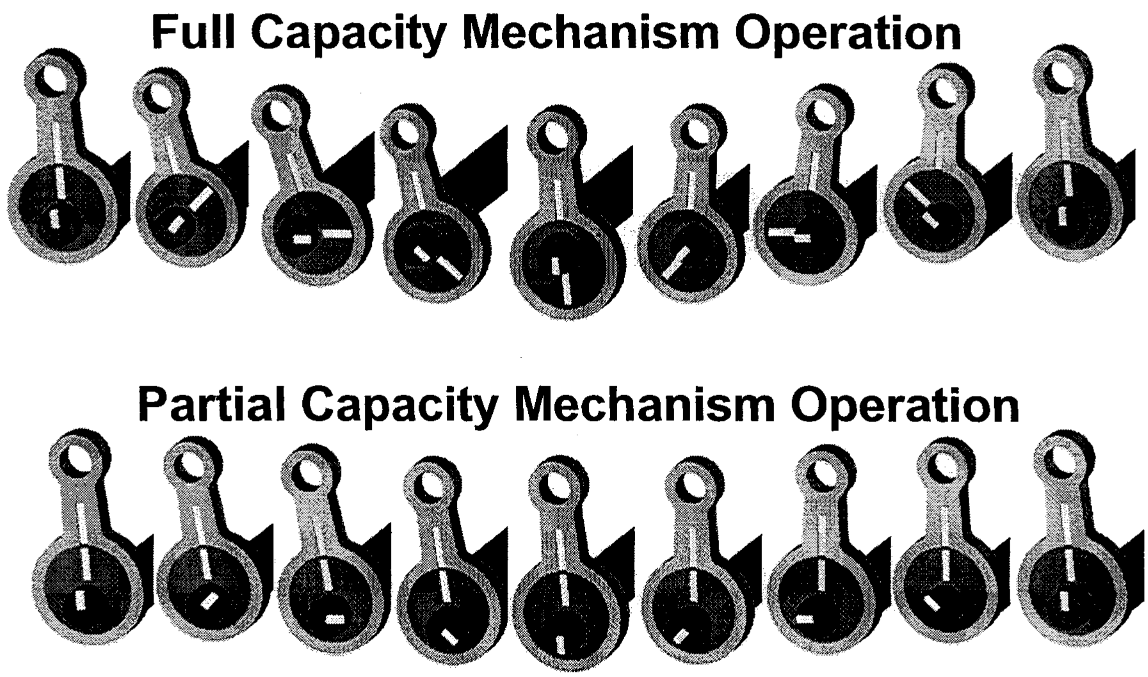

Figure 2

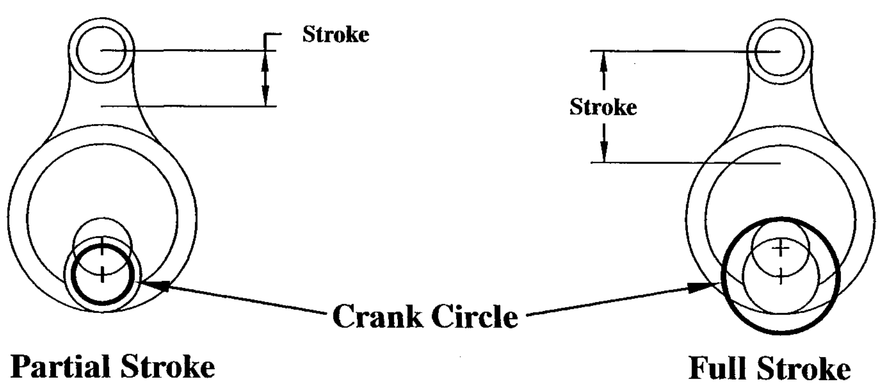

Figure 3

CONTROL OF THE TWO-STEP MECHANISM

One way to control the attachment of the throwblock to either the crankshaft (full capacity mode) or the connecting rod (partial capacity mode) is based on the direction of rotation of the mechanical. When the compressor spins in one direction, the throwblock attaches to the crankshaft for full capacity operation. When the mechanical spins in the other direction, the throwblock releases the crankshaft and attaches to the connecting rod for partial capacity operation. Thus, capacity can be controlled by reversing the direction of motor rotation.

Unmodulated single cylinder compressors generally use either an induction run or a permanent split capacitor (PSC) type of motor. The main winding is matched to the operating point of the compressor to provide maximum efficiency. When the operating point, or load, of the compressor changes, the efficiency of the motor falls dramatically. Thus, if the capacity of the compressor mechanical is reduced, the efficiency of the motor decreases from point A to point B as illustrated in Figure 4 below.

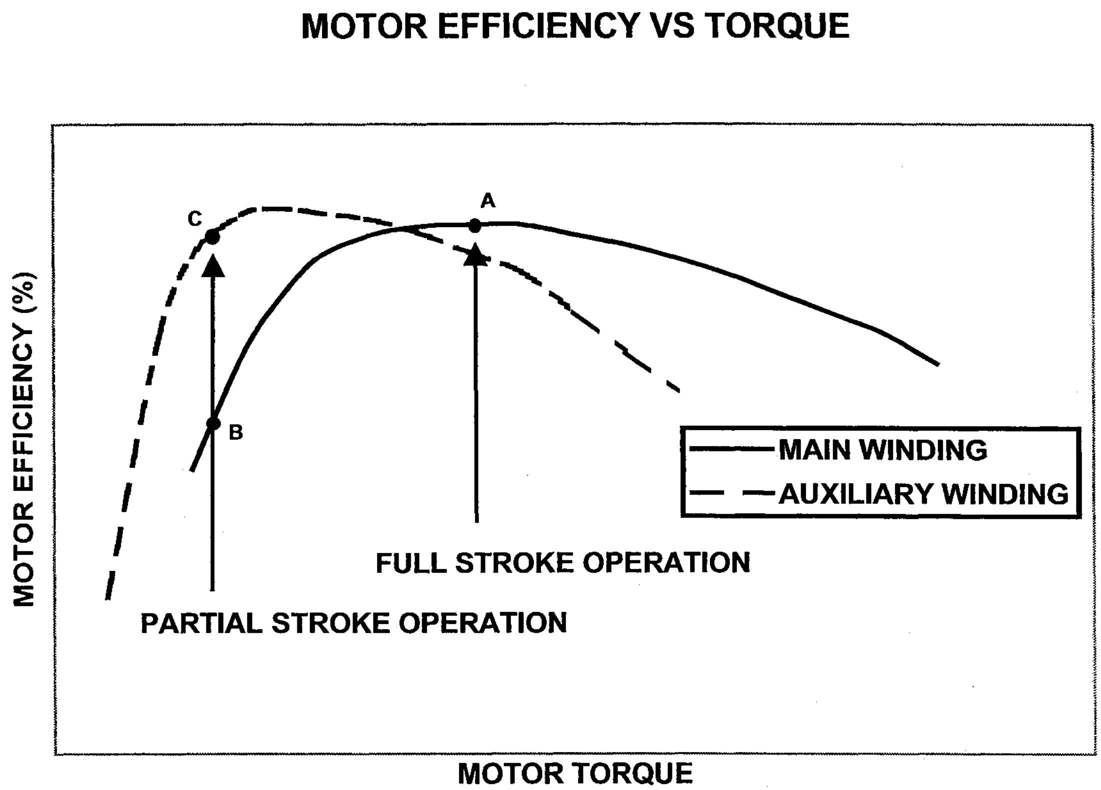

Figure 4

Fortunately, these motors have both a main winding and an auxiliary winding. By reversing these windings in the circuit, the direction of the PSC motor rotation can be reversed – that is, the main winding becomes the auxiliary winding, and vice versa. This is generally not possible with an induction run motor because the auxiliary winding is too small. By operating the compressor mechanical in full capacity in one direction of rotation, and partial capacity in the other direction, the efficiency of the windings can be optimized for two load points, shown as points A and C in Figure 4 above. Using the terms "run" and "start" windings, for the full capacity direction of rotation, the main winding is the "run" winding while the auxiliary winding is the "start" winding. For the partial capacity direction, the auxiliary winding is the "run" winding and the main winding is the "start" winding. Thus, the main winding is optimized for the full-capacity load point A and the auxiliary winding is optimized for the partial capacity load point C. The cost implications of matching a PSC motor to two load points are very small, and in some cases no changes are necessary at all. Also, PSC motors are only slightly more expensive than induction run motors.

IMPLEMENTATION OF A TWO-STEP COMPRESSOR

There are relatively few component changes necessary to implement a two-step modulation capability. The compressor mechanical requires the addition of the throwblock. The compressor electrical requires minimal changes to the motor to optimize part-load efficiency and allow the motor to reverse. This compressor can be installed as a drop-in replacement with no system changes, or improvements can be made to the system coils, expansion device and controls to optimize part-load operation.

Some possible control schemes using various levels of system integration are illustrated in Figures 5, 6 and 7. The first represents a "drop-in" replacement, the second illustrates a mechanical type of control system using bimetal thermostats and the third demonstrates an electronic solution wherein the compressor is mated tightly to the system controls.

Figure 5 below shows the use of a two-step compressor in the place of a standard compressor requiring no modifications to the existing system. The compressor has a timer mounted to it, and the electrical connections are the same as they would be for a non-modulating compressor. The system thermostat behaves the same way as before, and the compressor mode is based on run time. When the system thermostat first closes, the compressor starts in partial capacity mode. If the system demand has not been satisfied after a certain length of time, the timer stops the compressor, allows a time delay for pressure equalization, and restarts the compressor in full capacity mode. The compressor runs until the thermostat opens. This cycle is then repeated.

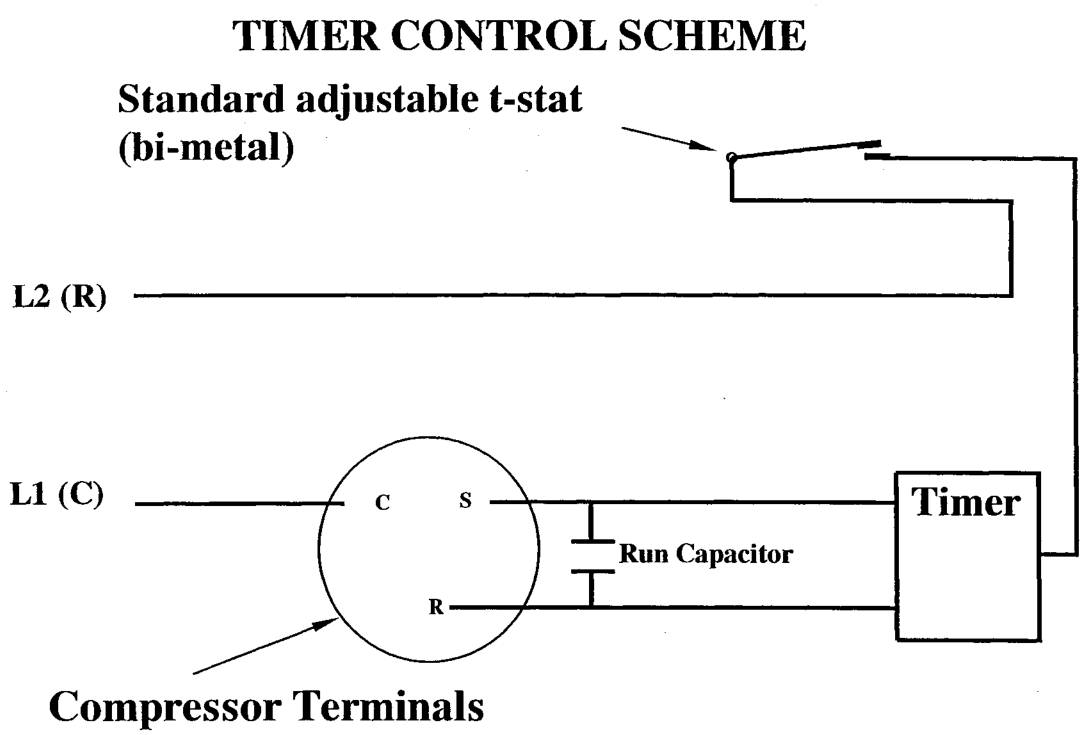

Figure 5

Figure 6 below illustrates a control scheme using a mechanical double-throw thermostat that controls compressor capacity used in conjunction with a standard mechanical thermostat to control cabinet temperature. When the cabinet is hot, both thermostats are closed and the compressor starts in full capacity mode. As the cabinet cools, the double throw thermostat switches the start and run windings, and the compressor runs in partial capacity mode until the cabinet temperature drops below the standard thermostat level. The compressor cycles at partial capacity unless it cannot satisfy the demand, in which case the cabinet temperature rises and the double throw thermostat switches the compressor to full capacity mode. A time delay must be included to prevent the compressor from starting against a pressure differential and also to allow motor rotation to stop, and there must be some hysteresis built into the double-throw thermostat to prevent the cabinet from warming above the partial capacity point during this delay.

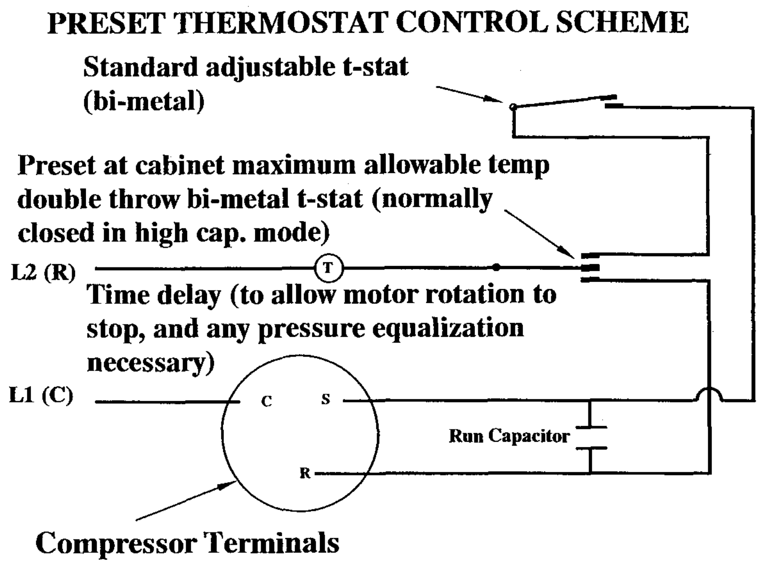

Figure 6

Figure 7 below shows an electronic thermostat that controls both compressor capacity and cabinet temperature. The temperature set points for the two capacity modes, the time delay and other features such as defrost algorithms and interrupt buttons for "sleep" or "ice making" features are all integrated into one controller.

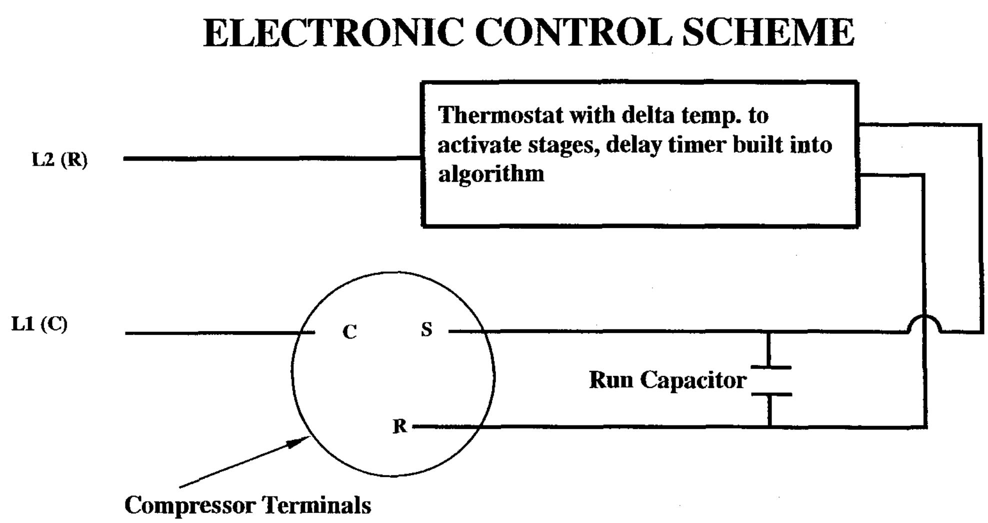

Figure 7

BENEFITS OF A TWO-STEP COMPRESSOR

Because standard compressors are sized for the highest loads a system will see, they provide too much capacity most of the time. This results in frequent cycling which is stressful to the system components. A two-step modulating compressor will allow the system to operate for a longer period of time at a reduced power level during steady-state operation while still providing the capacity to cool the system during times of higher loading. This permits less cycling and results in better reliability, better temperature control and less perceived noise.

The benefits to the system efficiency of two-step capacity modulation depend on the initial system efficiency and the amount of modifications that are made to the system. Testing with variable speed compressors shows that improvements in system efficiency range from 0% to 15% simply by installing a variable-speed compressor in place of a standard compressor. By tailoring the system coils, fans, thermostats and algorithms to a variable capacity compressor, improvements of up to 40% may be possible.

A manufacturing benefit of a two-step modulated compressor is deproliferation. By using such a modulating compressor in conjunction with various degrees of system and controls modification, a manufacturer can offer models of different efficiencies based on one chassis. For example, a low-end model might use a standard compressor, a mid-range model would use a two-step compressor with minimal system modifications, and a high-end model would use a two-step compressor with a control scheme and system components tailored to part-load operation. In this way many different models can be offered that use a similar cabinet and compenents.

Two-step modulation also provides the possibility of sales tools in terms of customer features. A high efficiency refrigerator that has a "Make Ice" button that changes the compressor mode to full capacity for a fast pull-down or to freeze water quickly provides tangible benefits to a homeowner. Alternatively, some commercial customers may be interested in a "Sleep" feature that keeps a vending machine in low-capacity mode during off-peak hours. Two-step modulation can add value to a product above and beyond reduced power consumption.

CONCLUSIONS

Two-step capacity modulation of a single cylinder compressor can be used to improve system efficiency through decreased power consumption, improve system reliability through decreased cycling and improve temperature control through longer run times. It can allow a manufacturer to offer new commercial and consumer features. Two-step capacity modulation can also reduce manufacturing proliferation by allowing several products of different efficiency levels to be built using the same chassis and slightly different control schemes. This can be done in a cost-effective manner and can be easily adapted to existing appliances.